# ESTCP
# Cost and Performance Report

(MR-200733)

## Underwater Simultaneous EMI and Magnetometer System (USEMS)

**February 2011**

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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Project: MR-200733

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| COTS | commercial off-the-shelf |
| DBT | depth below transducer |
| DoD | Department of Defense |
| EM | electromagnetic |
| EMI | electromagnetic induction |
| ESTCP | Environmental Security Technology Certification Program |
| GPS | Global Positioning System |
| JATO | jet-assisted take-off |
| MEC | munitions and explosives of concern |
| MSEMS | Man-Portable Simultaneous EMI and Magnetometer System |
| NMEA | National Marine Electronic Association |
| PLC | programmable logic controller |
| RPS | Rotor Position Sensor |
| RTK | Real-Time Kinematic |
| RTN | Real-Time Network |
| USACE | U.S. Army Corps of Engineers |
| USEMS | Underwater Simultaneous EMI and Magnetometer System |

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# 1.0 EXECUTIVE SUMMARY

## 1.1 TECHNOLOGY DESCRIPTION

Due to historical training and disposal activity, munitions and explosives of concern (MEC) exist in the marine environment in a variety of underwater topographies ranging from open waters to bays to port areas to lakes and ponds. Although the geophysical sensors used for MEC detection in the marine environment—magnetometers and pulsed electromagnetic (EM)—are the same as those used in the terrestrial environment, there is not a one-size-fits-all solution due to differences in sea state and water depth. The Underwater Simultaneous EMI and Magnetometer System (USEMS) is designed to survey shallow (one to three meter) water such as lakes, ponds, rivers, streams, coastlines, and obstructed areas where a larger cable-towed array is not able to navigate. USEMS consists of a 17 ft boat towing a towfish that houses an EM61 submersible coil and a total field magnetometer. The towfish is attached to the transom of the boat with a rigid carbon fiber boom whose rotational degrees of freedom are instrumented with encoders to directly measure its yaw, pitch, and roll relative to the back of the boat. The magnetometer and EM61 are operated concurrently via the interleaving technique developed and demonstrated under ESTCP projects MR-200208 and MR-200414.

## 1.2 OBJECTIVES OF THE DEMONSTRATION

In September 2010, USEMS was demonstrated at Plum Tree Island, VA, where it surveyed a shallow water test site and a deeper water test site, and acquired traverse data off Plum Tree Island. The objectives of the demonstration were to evaluate USEMS' ability to collect concurrent EM61 and magnetometer data in an actual MEC shallow water environment, and to collect data to be used to evaluate metrics related to the hydrodynamic stability of USEMS' submerged towfish, the ability of USEMS to maintain a constant height above bottom, the

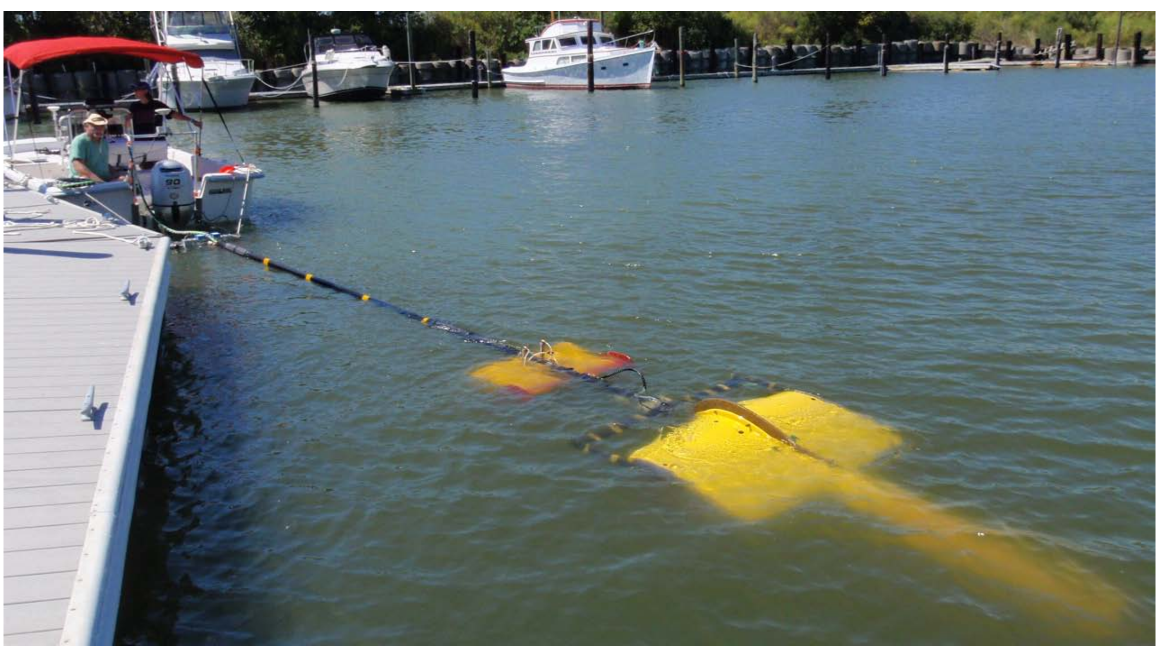

**Figure 1. USEMS dockside at Plum Tree Island.**

accuracy of the geodetically combined sensor and positioning data, the ability of USEMS to cover an area with data tracks, and the general ease of operation of the system.

## 1.3 DEMONSTRATION RESULTS

The objective of being able to survey at a planned height above bottom was met, with a standard deviation of ~19 cm from the planned height. In very shallow water (~1 m), the system had a vertical oscillation of approximately 50 cm. However, this oscillation vanished when the system was deployed in deeper (>2 m) water and thus is likely due to interaction with the boat motor's propeller wash. Objectives for the geodetic accuracy of located targets were met, with an average location error <37 cm and standard deviation <19 cm. Noise objectives were met for the magnetometer data, but not for the EM61 data. The magnetometer was effective at detecting objects at standoff distances of 0.5 m, 1.0 m, and 1.5 m off the bottom. The EM61 was effective at detecting objects at a standoff distance of 0.5 m off the bottom. The ability of the system to cover an area with planned data tracks improved over the course of the demonstration but fell short of the 95% coverage objective. The approximate cost to build a USEMS is $240,000. Approximate survey costs for USEMS and a two-person crew are $1440 per hectare.

## 1.4 IMPLEMENTATION ISSUES

After the demonstration, many changes were made to the boat wiring to lessen the coupling of noise into the EM61. We expect EM61 noise levels to be nominal on the next survey. The ability of the system to survey tightly spaced parallel tracks depends not only on wind and wave state but on operator experience and training, the location of the Global Positioning System (GPS) antenna that feeds the guidance system, and the guidance feedback to the operator. We have made changes that we expect to facilitate line following on the next survey.

# 2.0 INTRODUCTION

## 2.1 BACKGROUND

Due to historical training and disposal activity, MEC exist in the marine environment in a variety of underwater topographies ranging from open waters to bays to port areas to lakes and ponds. Although the geophysical sensors used for MEC detection in the marine environment—magnetometers and pulsed EM—are the same as those used in the terrestrial environment, there is not a one-size-fits-all solution due to differences in sea state and water depth. Cable-towed arrays are effective in large open areas, but may have difficulty operating in shallow or constrained areas. In project MR-200733, the USEMS deploys a single total field magnetometer and commercial off-the-shelf (COTS) EM61 submersible coil, with both sensors configured in a hydrodynamically smooth towfish. The towfish is rigidly attached behind a 17 ft Carolina Skiff via a 6 m boom whose angles are instrumented to provide a direct measurement of the sensors' locations. USEMS was demonstrated near Plum Tree Island (Hampton) VA in September 2010.

## 2.2 OBJECTIVE OF THE DEMONSTRATION

The requirements of the demonstration were to verify and validate:

- The hydrodynamic stability of USEMS' submerged towfish
- The ability of USEMS to maintain a constant height above bottom
- The accuracy of the geodetically combined sensor and positioning data
- The ability of USEMS to cover an area with parallel swaths
- The general ease of operation of the system.

To meet these objectives, we identified a shallow (chest-high) section off Plum Tree Island free of metallic clutter, emplaced a test plot with 14 pipes ranging from 1.5 to 4 inches in diameter, measured the locations of items in it with Real-Time Kinematic (RTK) GPS, and surveyed the test plot multiple times. We also surveyed a second deeper test plot where objects were placed but their precise locations were not directly measured with RTK GPS. Finally, we ran traverses off Plum Tree Island in areas of previously identified metallic contamination.

## 2.3 REGULATORY DRIVERS

The primary driver is the continued need to develop tools to detect underwater MEC. The documented use of a pole-mounted concurrent mag/EM system will allow other contractors to employ this technique.

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# 3.0 TECHNOLOGY

## 3.1 TECHNOLOGY DESCRIPTION

USEMS consists of the following major systems:

- Boat
- Boom with bridle and transom mount
- Towfish with geophysical sensors (magnetometer and EM coil)
- Dive planes for depth control
- Positioning sensors
- Topside electronics.

These are shown in Figure 2.

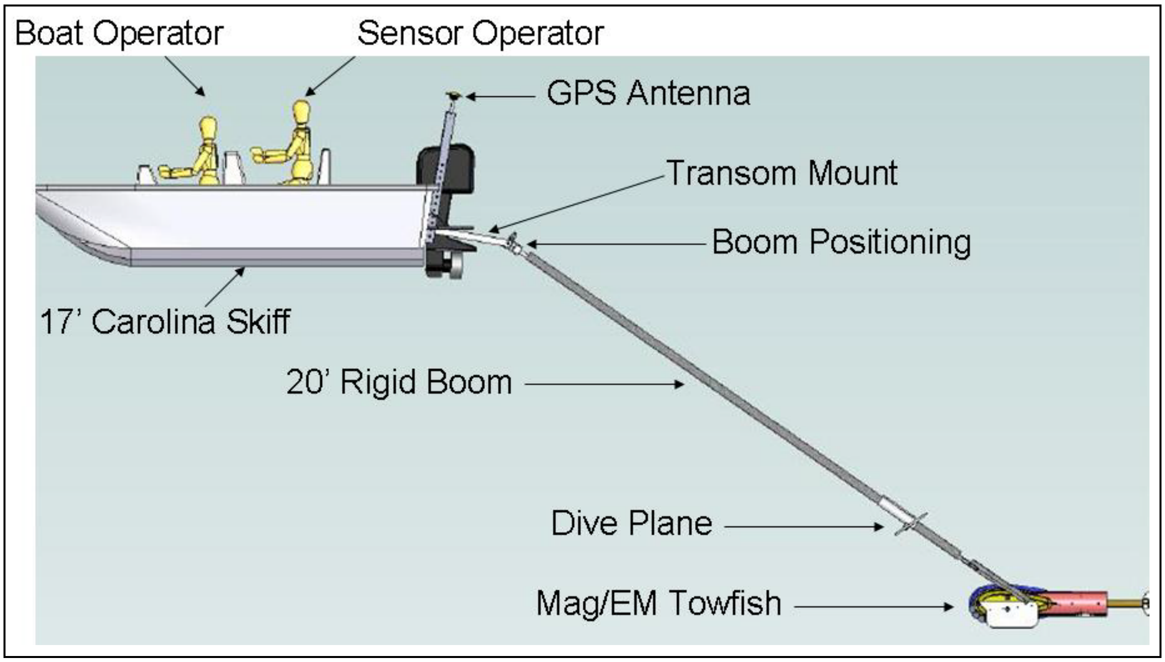


**Figure 2. USEMS schematic.**

The boat is a 17 ft Carolina Skiff with a V-shaped hull chosen for the shallow draft needed for USEMS' mission of shallow water deployment. A mount on the transom of the boat hosts the boom. The attachment point of the boom to the transom allows the boom to pivot freely in yaw (azimuth angle), pitch (incidence angle), and roll (twist).

The towfish contains a COTS EM61-S (submersible) coil and a Geometrics G-882 total field magnetometer with integrated depth and altitude sensors. The G-882 magnetometer was special-ordered from Geometrics with a Larmor output, as the technical approach of interleaving magnetometer data between EM61 pulses requires the interleaving electronics to have access to the magnetometer's Larmor signal. The towfish is attached to the wet end of the boom via a rigid bridle.

Hydraulically driven dive planes on the boom are used to drive the towfish up and down in the water column to adjust the desired height off the bottom. The dive planes are operated manually via an operator-driven joystick.

Positioning sensors include (a) a dual-antenna GPS in the boat, which provides the location of the transom as well as the boat's heading; (b) an inclinometer in the boat measuring the boat's pitch and roll; (c) three Rotor Position Sensor (RPS) at the boom's transom attachment point measuring the boom's yaw, pitch, and roll; (d) an RPS at the point where the bridle attaches to the end of the boom, measuring the bridle's yaw; (e) an inclinometer in the fish, measuring its pitch and roll; and (f) a depth sensor and an altimeter in the fish. An ancillary depth sensor is deployed in the boat to measure the depth of the water being entered. The actual positioning calculation is performed in post-processing.

Topside electronics include the COTS EM electronics console, the custom man-portable interleaving electronics that interleave the magnetometer data between EM61 pulses (sampling the magnetometer only when the EM61 is quiet), a COTS data acquisition computer running Geometrics' commercial MagLog data acquisition software that acquires and time-stamps all sensor data, a COTS depth profiler that also provides general marine navigation support, and a COTS track guidance device.

## 3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The USEMS technology has three primary advantages over other marine metal detectors. The first is that, because the sensors are affixed via a rigid boom instead of towed with a cable, USEMS has the ability to position a magnetometer and an EM coil close to the bottom in relatively shallow constricted areas. The second advantage of the technology is that, because the boom is rigid and all its rotational degrees of freedom are instrumented, the positional uncertainty should be substantially less than with a cable-towed system. The third advantage of the technology is that both magnetometer and pulsed EM data are acquired in a single survey pass, allowing for detection of nonferrous or low-ferrous objects.

Limitations of the technology are that USEMS' 6 m boom limits its survey depth to about 3.6 m, and that the EM61's 1 m swath width requires multiple closely spaced survey lines for full coverage. Experience at the Plum Tree Island demonstration shows that, because USEMS uses a small (17 ft) boat, the ability to follow 1 m planned traverses is influenced by wind, wave, currents, and wake, though pilot experience can significantly minimize this limitation. In addition, the small open boat chosen for USEMS' mission of shallow water surveying limits deployment in sea states higher than 0 or 1 (calm or light chop).

# 4.0 PERFORMANCE OBJECTIVES

The objectives of the demonstration were to verify:

- The hydrodynamic stability of USEMS' submerged towfish
- The ability of USEMS to maintain a constant height above bottom
- The accuracy of the geodetically combined sensor and positioning data
- The ability of USEMS to cover an area with data tracks
- The general ease of operation of the system.

Table 1 is a result of these heuristic objectives.

**Table 1. Performance objectives.**

| Performance Objective | Metric | Data Required | Success Criteria | Criteria Met? |
|---|---|---|---|---|
| **Quantitative Performance Objectives** | | | | |
| Towfish is hydrodynamically stable. | Absence of periodic motion creating deviation from linear towed motion | • Dynamic survey data | Amplitude of periodic horizontal and vertical motion <20 cm | Horizontal: Yes, <~5 cm<br>Vertical in deeper water: Yes , <~5 cm<br>Vertical in shallow water: No, ~50 cm, probably due to prop wash) |
| System can maintain a constant height above bottom. | Deviations from desired height above bottom | • Dynamic survey data | Standard deviation <50 cm | Yes, standard deviation <19 cm |
| Geophysical measurements are geodetically accurate. | Average error and standard deviation in northing and easting for ground truth items | • Geodetic coordinates of emplaced test plot objects<br>• Dynamic survey data over test plot objects<br>• Analysis of survey data | $\Delta$N and $\Delta$E <50 cm<br>$\sigma$N and $\sigma$E <1 m | Yes,<br>$\Delta$N and $\Delta$E <37 cm<br>$\sigma$N and $\sigma$E <19 cm |
| USEMS system noise is similar to MSEMS system noise. | Standard deviation of noise | • Dynamic survey data without targets present | $\sigma$USEMS noise $\leq$1.2 times $\sigma$MSEMS | Mag: Yes, 0.06<br>EM61: No, 18.5 |
| Track guidance system is usable for area surveys. | Oasis missed area | • Dynamic survey data | <5% missed area | No, 21%, but this is attributed mostly to lack of pilot experience. The track guidance system functioned to specification. |
| **Qualitative Performance Objectives** | | | | |
| System is operable by two-man crew. | Operator observations | • Time spent setting up the system and collecting dynamic survey data | All required functions can be executed by boat pilot and fish operator. | Yes |
| Equipment layout and information allows operators to do their jobs. | Operator observations | • Time spent collecting dynamic survey data | Boat pilot and fish operator are presented with information sufficient for them to perform their jobs. | Yes, but can be further improved with guidance computer |

MSEMS – Man-Portable Simultaneous EMI and Magnetometer System

Below is a brief discussion on objectives that were not met. A longer discussion is included in Section 8.

**Hydrodynamic Stability:** Data from the shallow test plot showed a vertical oscillation of approximately 50 cm. Because no such oscillation was seen in data from the deep test plot, it is believed that the towfish may have been interacting with the propeller wash created by the boat's motor. Using a jack plate to raise the motor may solve the problem.

**Noise:** Surprisingly high levels of noise were seen in the EM61 data. After the demonstration, the EM61 coil and cable were submerged in a salt water tank. Noise levels were nominal, indicating that the problem was not in the sensor and was instead systemic in nature. Several sources of noise were identified in the boat and EM61 power and data wiring. These have been corrected, and we expect EM61 noise levels to be nominal on the next survey.

**Track Guidance and Line Following:** The ability to follow tightly spaced (1 m) lines in a small boat requires calm wind and water, an experienced operator, proper guidance tools, and a GPS antenna located in the bow of the boat to reduce perceived operator lag. These factors all affected line-following performance at the demonstration. After the demonstration, we relocated the GPS antenna to the bow of the boat, and outfitted the boat with a computer running guidance software and a touch screen at the boat operator's fingertips.

# 5.0 SITE DESCRIPTION

## 5.1 SITE LOCATION AND HISTORY

The demonstration was conducted at Plum Tree Island, near the former Plum Tree Island bombing range in Virginia. The site was selected because it met the criteria in the white paper submitted last year to the Program Office (MR-200733, Requirements for a Successful Demonstration). The Plum Tree Island site was sufficiently shallow to use the system; it was close to shore with easy access; it had a relatively flat sandy bottom; and it was of interest to U.S. Army Corps of Engineers (USACE) because it is an active remedial investigation/feasibility study site. The site's location is shown on the maps in Figures 3 and 4.

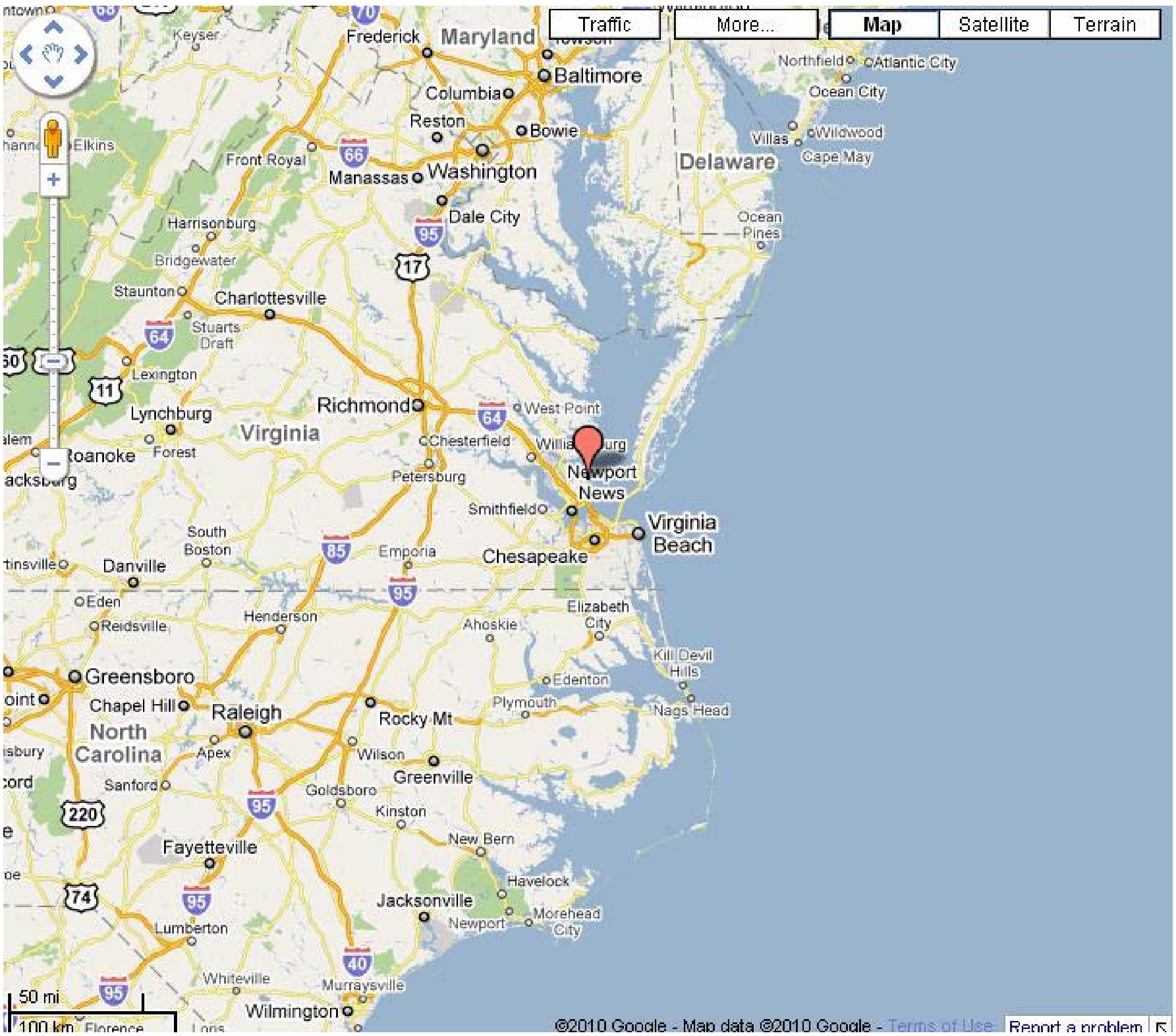


**Figure 3. Location of Plum Tree Island site (zoomed out).**

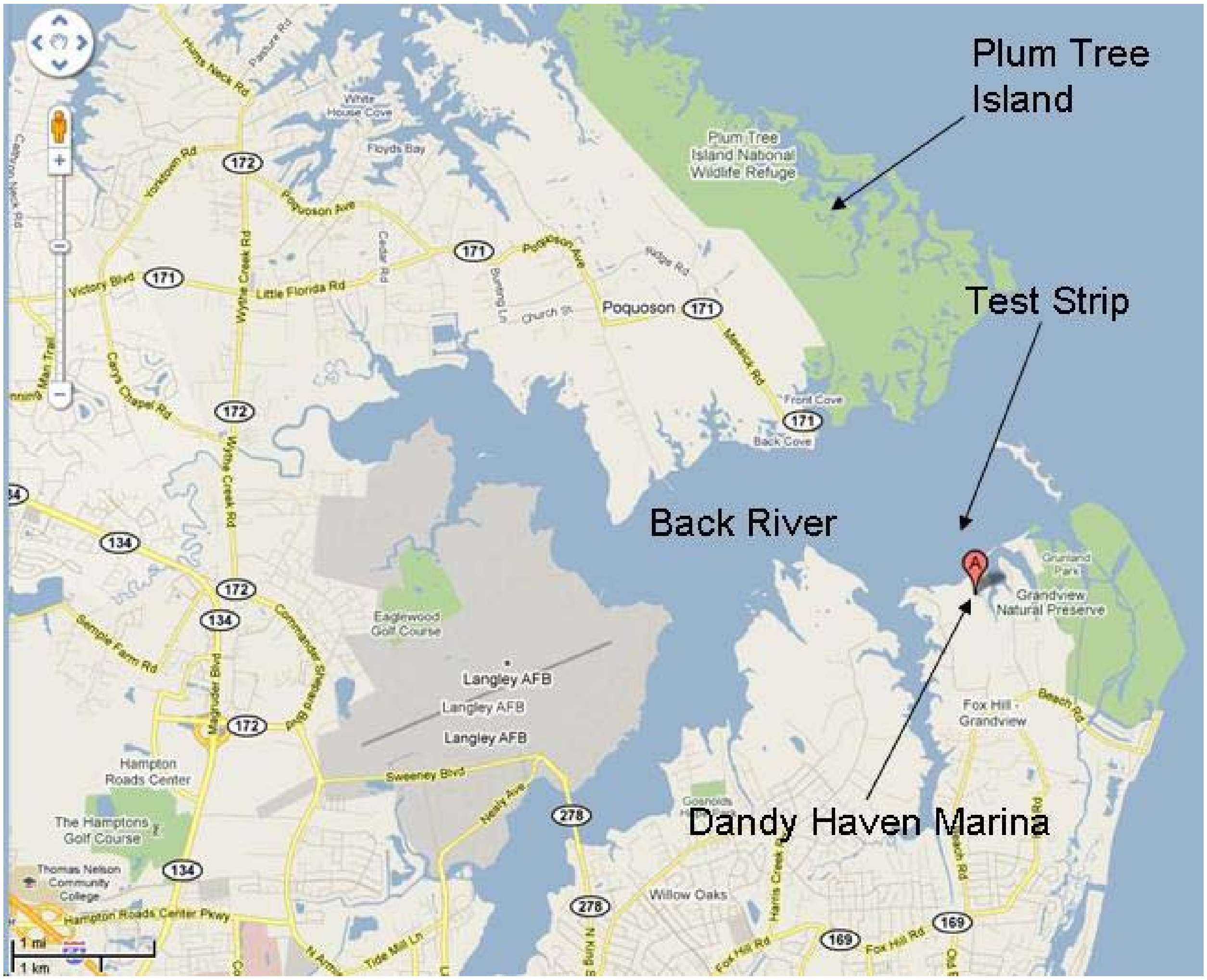


**Figure 4. Location of Plum Tree Island site (zoomed in).**

Plum Tree Island is situated on the southwestern corner of the Chesapeake Bay near the City of Poquoson, VA. It was owned by the Department of Defense (DoD) from 1917-1972 and was used for aerial bombardment and gunnery practice into the late 1950s. In 1972 it was transferred to the U.S. Fish and Wildlife Service. Today Plum Tree Island is one of four National Wildlife Refuges in the Eastern Virginia Rivers National Wildlife Refuge Complex.

## 5.2 SITE GEOLOGY

The site has a sandy bottom. The geology was benign to both the magnetometer and the EM61.

## 5.3 MUNITIONS CONTAMINATION

There is a high probability of the presence of MEC on the eastern sections of Plum Tree Island. During a previous survey, onshore cleanup efforts, guided by the results of geophysical transects and grids, identified a wide variety of MEC and munitions debris, including small arms, 50 pound bombs, 5-inch rockets and jet-assisted take-off (JATO) bottles. A shoreline sweep for surface items also uncovered 263 JATO bottles, along with occasional bomb and rocket parts. Additionally, an underwater EM transect survey conducted by USACE in 2009 resulted in the likely presence of buried metallic objects, with the largest concentration off the southeast corner of the island.

# 6.0 TEST DESIGN

## 6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The conceptual experimental design was to identify a flat, shallow (chest-high), metallically uncluttered area, construct a test plot approximately 10 m × 100 m of pipes of four sizes simulating four ordnance types in their most and least favorable orientations, emplace the objects at low tide without the use of divers, shoot in the locations carefully with GPS, then survey the test plot with USEMS at low tide and at high tide, at several different heights above bottom, and at several different survey speeds to allow evaluation of the system's geolocation accuracy in varied orientations by comparing the calculated and actual object locations using the changing boom orientation recorded by the system's positioning sensors. The fact that the test plot had cross-track extent (as opposed to a strictly linear test strip) made the survey require multiple passes, allowing us to evaluate the system's ability to cover an area with parallel data tracks. The conceptual experimental design included identifying a deeper section of water and testing the system's bottom-following ability, but without rigorously emplacing a second deeper emplaced test plot, as the divers needed for deep water would substantially impact the cost of the demonstration. We planned to emplace several objects in the deep test plot by maneuvering the boat within a meter of the planned location and dropping them over the side. The shallow and deeper plots are shown in Figure 5, along with other traverses we ran off Plum Tree Island.


**Figure 5. Shallow and deep test plots (blue) and traverses run off Plum Tree Island (red).**

## 6.2 SITE PREPARATION

Other than emplacement of the test plot (described in Section 6.1) and a background survey to ensure the absence of metallic clutter, there was no site preparation.

## 6.3 SYSTEM SPECIFICATION

A general system description was included in Section 3.1. Sampling rates and other relevant parameters are listed below.

### 6.3.1 Pulsed Induction Sensor

The EM61 MKII pulsed induction electronics are located topside and connected to a single 1 × 0.5 m EM61-S (submersible) coil in the towfish, with the long axis of the coil oriented across the width of the towfish. The electronics are employed in their COTS mode using time gate values of 256, 406, 706, and 1306 $\mu$sec. Data acquisition is controlled by MagLog "soft-triggering" the EM61. EM61 data are acquired at a 10 Hz rate.

### 6.3.2 Total Field Magnetometer

Data from the Geometrics G882 magnetometer are acquired, interleaved between EM61 pulses using the interleaving electronics from project MM-0414. This allows the Larmor signal from the magnetometer to be sampled every 13.3 ms, for a 5 ms duration, just before the next EM61 transmit pulse begins. The period counter in the interleaving hardware converts the frequency-based Larmor signal to nanotesla and outputs it in an ASCII comma-delimited format. Because sampling of the magnetometer data is interleaved between EM61 pulses, the magnetometer sampling rate is the same as the EM61 internal pulse repetition rate, namely 75 Hz. The ASCII data stream is then read and stored in MagLog. The magnetometer and the EM61 coil are both located in the towfish. Prior work on MM-0414 determined that, even with interleaving, a 4 ft coil-to-magnetometer separation is necessary to ensure that the Larmor signal hasn't gone out of range from the EM pulse. USEMS employs a safety factor; the magnetometer's sensor head is located 5 ft behind the edge of the EM61-S coil.

### 6.3.3 GPS

A Trimble MS860II GPS receiver is installed in the boat, with antennas mounted at the bow and stern along the centerline that intersects with the pivot point of the boom. The GPS is operated in RTK mode. To eliminate the problem of where to set up a base station for a marine survey, we employed a subscription-based RTK correction service implemented via a cellular modem over a Real-Time Network (RTN). A National Marine Electronic Association (NMEA) GGK string containing the time and the location of the stern antenna are output at 10 Hz and recorded by MagLog. A second string, the NMEA AVR string containing the heading, are output at 10 Hz and recorded by MagLog.

### 6.3.4 Boat Inclinometer

The roll and pitch of the boat are measured using a gravity-referenced inclinometer outputting at a 10 Hz rate and recorded by MagLog.

### 6.3.5 Boom Rotary Position Sensors

The yaw, pitch, and roll of the pivot point at the topside of the boom are measured using rotary positioning sensors integrated directly into the pivot. The sensors are laser-sighted so that they read zero when the boom is straight behind the two GPS antennas and is parallel with the mounting surface for the boat inclinometer. The RPS are read by a programmable logic controller (PLC), which outputs data to MagLog at a 10 Hz rate.

### 6.3.6 Bridle Yaw Rotary Position Sensor

A fourth RPS is mounted where the bridle is attached to the wet end of the boom. It is laser-sighted to read zero when the bridle is straight behind the boom. This RPS is also read by the PLC that outputs to MagLog at a 10 Hz rate.

### 6.3.7 Fish Inclinometer

The roll and pitch of the towfish are measured using a gravity-referenced inclinometer outputting at a 10 Hz rate and recorded by MagLog.

### 6.3.8 Fish Depth and Altitude

Along with the magnetometer itself, the COTS Geometrics G882 contains a depth transducer and an altitude sonar. These are output (along with non-interleaved magnetometer data) at 10 Hz and recorded by MagLog. The fish altitude is watched by the fish operator who uses a joystick to control the hydraulically actuated dive planes to try to keep the fish at a constant height off the bottom.

### 6.3.9 Boat Water Depth Transducer

A depth transducer is mounted on the boat, and outputs the NMEA DBT (depth below transducer) string at 1 Hz. These data are used by the fish operator to alert him of the water depth that the boat is entering. Although these data are recorded by MagLog, they are not used in the geolocation calculation.

## 6.4 DATA COLLECTION

### 6.4.1 Scale

We used the depth sensor in the boat to identify a small plateau that was long and wide enough to host the test plot and sufficiently shallow to allow emplacement of the test plot at low tide. The water depth of this area was only chest high at high tide and thus did not allow for testing USEMS for varying height above bottom.

**Figure 6. Bathymetry data used to identify and lay out shallow water test plot.**
Large squares are 100 m.

The sections of standard Schedule 40 steel pipe used for the test plot objects are listed in Table 2. These pipe objects are shown next to the objects they simulate in Figure 7.

**Table 2. Standard pipe thicknesses.**

| Common Name | Outside Diameter (inches) | Wall Thickness (inches) | Length (inches) |
|---|---|---|---|
| 4-inch | 4.5 | 0.24 | 18 |
| 3-inch | 3.5 | 0.22 | 18 |
| 2-inch | 2.375 | 0.15 | 12 |
| 1.5-inch | 1.875 | 0.15 | 12 |

**Figure 7. Pipe simulants for 60 mm, 81 mm, 2.75 inch, and 105 mm items.**

All objects were emplaced by walking to the planned location using an RTK GPS, placing the object at that location, then recording the location of the center of the object with the GPS. The first object is a pair of 6-m-long pipes laid end to end to act as a start-of-track fiducial. The objects along the center line are 4-, 3-, 2-, and 1.5-inch pipes in their most-favorable (vertical) and least favorable (horizontal cross-track and horizontal down-track) orientations, for a total of twelve on-center objects. Four additional objects are located off-center (two 2-inch and two 1.5-inch pipes). The down-track separation of all other objects is seven meters.

In addition to the shallow water test plot, a deeper water test plot was used. This consisted of four objects (two 4-inch and two 3-inch pipes) placed approximately 10 m apart in water approximately 2 m deep along a line aligned north-south. Because the water was too deep for a person to stand (either to emplace the objects or measure their placement), emplacement was performed by anchoring the boat upwind of each location, letting out line to float the boat to the approximate northing location and using a small powered skiff to swing the boat laterally to the approximate easting location. When northing and easting were within a meter of the desired location, the object was dropped. Because the objects needed to be retrieved, a rope with a buoy was tied to each object. However, because the rope and buoy could snag on the towfish or propeller, a scheme was devised to weigh down the lines with nonmetallic weights (flowerpots) and stretch the lines laterally westward so the buoys would float up about 10 m west of the objects. Despite the J-shaped lines, the line to one object was snagged on the first day of deep testing, and the object was dragged outside the test plot. Subsequent analysis was performed on the remaining three objects.

### 6.4.2 Sample Density

The cross-track line spacing was 1 m. The boat driver drove the boat at a speed high enough to mitigate drift from wind, wave, currents, and wake, but low enough not to drive the fish into the bottom. The average speed on the shallow test plot was approximately 1.2 m per second, resulting in a down-track EM61 data spacing of approximately 12 cm, and a down-track magnetometer spacing of approximately 1.6 cm.

### 6.4.3 Quality Checks

All geophysical sensor and positioning sensor data were displayed on the MagLog computer and examined in real time by the fish operator. Visual and audible alarms were employed to alert the fish operator if data output ceased from any sensor or was outside an acceptable range. In this way, MagLog alerted the operator if the GPS lost its link with the base station, or collected data that were not of RTK fixed integer quality, or if the GPS clock board malfunctioned or lost its timing base.

### 6.4.4 Data Summary

Eight sets of data over the shallow water test plot and 15 sets of data over the deepwater test plot were acquired. The data reside at SAIC in Waltham MA, on the server and archived to DVD. The data also reside at USACE Huntsville. The data exist in their raw form of MagLog-stored time-stamped ASCII files, as geolocated ASCII files, and as Oasis databases.

## 7.0 DATA ANALYSIS AND PRODUCTS

The data flow of USEMS has the magnetometer, EM61, GPS, rotary positioning sensor, inclinometer, altimeter, and depth sensor data streaming into MagLog, time-stamped with GPS time and stored in files. All raw files are ASCII except the EM61 data file. For analysis, all files are read by a piece of preprocessing software ("usemsproc") which time-correlates the geophysical and positioning data, performs the geodetic calculation, notch-filters the magnetometer data, background-levels the magnetometer and EM61 data, and writes out ASCII leveled magnetometer and EM61 data files that are then read into Oasis. This data flow is depicted in the figure below.

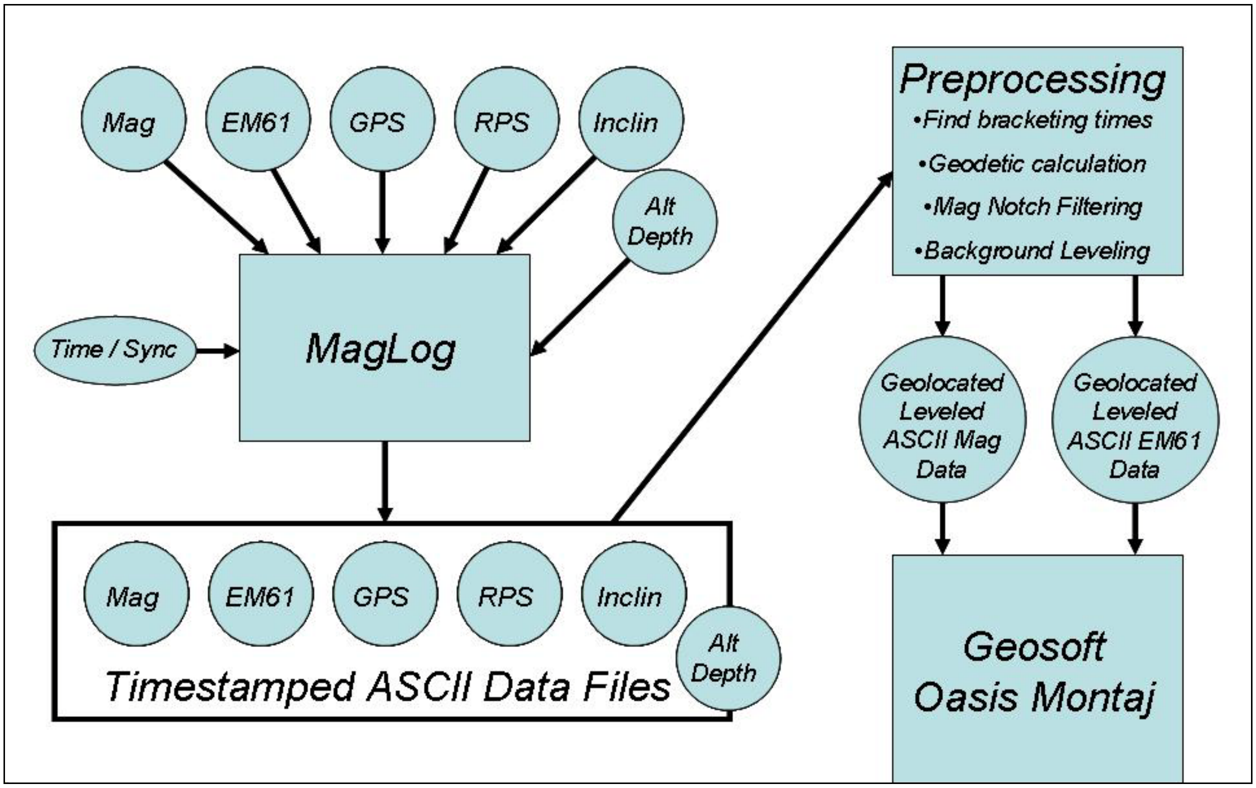


**Figure 8. USEMS data flow.**

### 7.1 PREPROCESSING

All preprocessing occurs in the program usemsproc.

**Notch Filter:** Because USEMS acquires concurrent mag and EM61 data, the magnetometer sampling occurs at the EM61's 75 Hz pulse repetition rate. At 75 Hz, the ubiquitous 60 Hz hum from ambient electrical activity aliases flawlessly at 15 Hz. A de-spiking median filter is first applied to the time-series magnetometer data on each line to remove spurious values. A notch filter is then applied to the magnetometer data to remove the 15 Hz aliased signal.

**Background Leveling:** A de-median filter with a 6-second window is applied to both the magnetometer data and the EM61 data to determine a background value. This value is then

subtracted from the data, resulting in dynamic background leveling. This removes instrument drift from the EM61 data. It also removes the effect of geology and any small effect of the signature from the boat or its motor from the magnetometer data.

**Forward Kinematic Model:** All data acquired by MagLog are time-stamped using the GPS time (the MagLog computer contains a GPS clock card). The magnetometer and EM sensor updates are read. For each sensor update, the time is examined, the closest set of bracketing times of the positioning sensors (GPS, RPS, and inclinometer values) are found, and a new positioning value is interpolated across the time gap. A forward kinematic model is then employed that factors in the appropriately interpolated positioning values for the position, roll, and pitch of the back of the boat; the roll, pitch, and yaw of the boat; the angles of the boom; and the roll, pitch, and yaw of the fish.

## 7.2 DATA PRODUCTS

The data in their raw form are stored in eight files created by MagLog. There is one space-delimited file for each of the input sensors depicted in the figure above. These files are ASCII except for the EM61 MKII file, which is binary. Each entry in each file is time-stamped by MagLog using the time derived from the computer's GPS clock card. The preprocessing software reads these input files and outputs two files meant for import into Geosoft Oasis Montaj —a geodetically registered magnetometer file and a geodetically registered EM61 data file.

# 8.0 PERFORMANCE ASSESSMENT

## 8.1 ABILITY OF USEMS TO CONCURRENTLY COLLECT UNDERWATER EM61 AND MAGNETOMETER DATA

Because the capability of the hardware to concurrently collect EM61 and magnetometer data had already been demonstrated on several ESTCP projects, the ability of USEMS to do this underwater was not in doubt and thus was not a formal objective. Nonetheless, the figures below show a set of concurrently collected EM61 and magnetometer data from the shallow water test site. The black circles represent the ground truth of the emplaced pipes. The circle without an anomaly in the center of the track represents a pipe that was snagged earlier and not replaced.

**Figure 9. Concurrently collected magnetometer data (±50nT) on shallow water test plot, 0.5 m high.**

**Figure 10. Concurrently collected EM61 gate 3 data (±50mV) on shallow water test plot, 0.5 m high.**

## 8.2 HYDRODYNAMIC STABILITY

We found that, on all data from the shallow water test site, there is a non-trivial amount of vertical oscillatory motion—approximately 40 to 50 cm peak-to-peak, with a period of approximately 6 seconds. This oscillatory motion is present in the fish depth transducer, the fish altimeter, the fish inclinometer, and the boom pitch RPS, and is not present in the boat water depth sensor or the boat inclinometer. This indicates that this particular motion is not an artifact of wave action. The metric for this objective (the amplitude of periodic motion) was 20 cm in both the vertical and horizontal directions. Although there is no evidence of periodic motion in the horizontal direction, the motion exceeds the criteria in the vertical direction. Thus, the success criteria were not met on the shallow test site. However, this vertical periodic motion of the fish *is not present* in data from the deepwater test site. Note that the difference in water depth between the shallow water test plot and the deepwater test plot is not terribly great. Surveys over the shallow test plot had the water depth vary as a function of tide from 0.87 m to 1.2 m; the

surveys over the deep test plot had the water depth vary from 1.7 m to 2.5 m. Thus, the average additional water depth in the deep test plot is only approximately 1 m greater than in the shallow water test plot. Because of the rapid falloff in this oscillation as a function of water depth, we believe that the oscillation is being produced by the interaction of the fish with the propeller wash of the boat's motor. Raising the motor with a jack plate may solve the problem.

## 8.3 MAINTAINING A CONSTANT HEIGHT ABOVE BOTTOM

Because the shallow test plot was so shallow, we surveyed it near high tide and let the fish ride close to the surface. This meant that the height above bottom was not an independently adjustable variable. However, in the deepwater test plot, the height was an independently adjustable variable. For the deep test plot, on all runs, the mean height is within 10 cm of the desired height. The worst standard deviation is 19 cm, and the average standard deviation is 12 cm. Thus the success criteria (standard deviation <50 cm) were met.

## 8.4 GEODETICALLY ACCURATE SURVEY MEASUREMENTS

### 8.4.1 Analysis of Shallow Water Test Plot

#### 8.4.1.1 Geolocation Accuracy of EM61 Data

Because no data set contained one line that went directly over every object, a method was devised for finding the closest approach. The geolocated EM61 data from each data set were read into Oasis, and the "pick peaks along line" tool was used. A 10 mV detection threshold on gate 3 was selected, as this threshold was above the noise floor and reliably picked targets whose line paths appeared to cross over or near the ground truth locations. The autopicked targets were written out to file and then read into a piece of software that, for each ground truth location, found the closest autopicked target location. If the closest target location to a ground truth location was greater than one meter away, we examined the data to find the cause, and saw that the closest sensor path was sufficiently far from the target that there was no signal that stood out above the noise. We regarded these as a misses and did not include them in the statistics. The distance from ground truth, the down-track offset, and cross-track offset were recorded in a table. This was done, in each of the eight shallow water data sets for each target. Average distances and offsets were then calculated for each data set. The aggregated average was 0.37 cm, and the aggregated standard deviation was 0.19 cm. Thus the test criteria (average <50 cm, standard deviation <1 m) were met.

#### 8.4.1.2 Geolocation Accuracy of Magnetometer Data

Because the dipolar response of the magnetometer is more complex than the unipolar response of the EM61, the method of extracting the coordinates of the strongest peak that was employed to determine the geolocation accuracy of the EM61 data was not appropriate for the magnetometer data. Instead, we used Oasis' UxAnalyze tool to fit magnetic dipoles to the magnetometer data at the target locations in the test strip. UxAnalyze rejected some of the strongest dipoles. These rejected items were not included in the statistics. The aggregated average is 30 cm; the aggregated standard deviation is 19 cm. Thus the test criteria (average <50 cm, standard deviation <1 m) were met.

### 8.4.2 Analysis of Deepwater Test Plot Data

Because the water depth in the deepwater test plot was too deep to stand up in, objects were emplaced by dropping them over the side of the boat within approximately a meter of their planned locations. Because these objects were not shot in with an RTK GPS like objects in the shallow water test plot, their actual ground truths are not known. Four objects were dropped, but early in the survey, despite J-shaped lines attached to buoys intended to avoid snagging, one object was snagged and dragged to the side. Thus all data in the deep test plot contain three objects.

#### 8.4.2.1 Geolocation Accuracy of EM61 Data

The deep test plot was surveyed at 0.5 m, 1.0 m, and 1.5 m standoffs, but the runs that had substantial signal above noise in the EM61 gate 3 data were those acquired at a fish height of 0.5 m. For these data sets, we calculated the target locations the same way we did for the shallow test plot—by using Oasis to automatically pick the peaks along the profiles, by selecting the strongest peaks, and calculating their locations. The ground truths are not known, but the spread of northing and easting values was calculated. All standard deviations were less than 0.42 cm, which is well within our success criteria.

#### 8.4.2.2 Geolocation Accuracy of Magnetometer Data

In the magnetometer data, the signal over the targets is strong not only in the 0.5 m height data but also the 1.0 m and 1.5 m height data. This is not the case in the EM61 data, where only the data acquired at 0.5 m standoff produced viable signal to noise. Thus, the deep magnetometer data present a richer data set than the deep EM61 data. We performed the same analysis on the deepwater magnetometer data that we did on the shallow water magnetometer data—we fit the anomalies with UxAnalyze to extract their locations. As with the EM61 deep test plot data, we calculated the spread of northing and easting values. All standard deviations were less than 0.44 cm, which is within our success criteria.

## 8.5 NOISE

We compared noise in the magnetometer data acquired at Yuma with MSEMS and at Plum Tree Island with USEMS. In both data sets we selected a portion of a survey line acquired over a section of the test plot, where there were neither emplaced targets nor obvious clutter, and extracted the statistics from the background-leveled magnetometer data. The standard deviation of the noise in the USEMS magnetometer data is more than an order of magnitude less than that of the MSEMS data, meeting the success criteria, and clearly indicating that the interleaving is functioning as designed and that USEMS is collecting high-quality magnetometer data between EM61 pulses.

Similarly, we compared EM61 data acquired at Yuma with MSEMS and at Plum Tree Island with USEMS. Because EM61 noise varied substantially in the USEMS data for comparison purposes we averaged the noise statistics from an object-free section of all eight shallow water tests. The EM61 data from USEMS is substantially noisier than the MSEMS data, particularly in the earlier time gates. The standard deviation of the noise in the USEMS data is approximately

18.5 times that of the MSEMS data, which does not meet our objective. Although the noise is much lower on the later time gates than on gate 1, it is still far larger than what is commonly experienced on EM61 terrestrial survey. This did not render USEMS' EM61 useless, but it did require targets to have higher signal than on terrestrial surveys to stand out from the noise. This in turn required the towfish to be close to the bottom to achieve EM61 detection.

After the Plum Tree Island demonstration, we methodically tested the EM61 to isolate the source of noise. We took the EM61 coil and cable out of the towfish, submerged it in a salt water tank, and acquired data with a COTS EM61. Noise levels were nominal, indicating that there was not a problem such as water intrusion into the coil and that the noise source was likely systematic in origin. We discovered that:

- The battery powering the EM61 had an in-line connector to allow for quick disconnect. This proved to be a source of noise if touched or jostled. The connector was removed and the EM61 was wired directly to the battery.
- Even though the EM61 was powered with an isolated battery, there were ground loops formed through ground wires in serial ports. We isolated these with optical isolators.
- The boat had been wired with a shared ground bus. This meant that the power feed to high-amperage devices such as the computer and GPS did not have the benefit of noise-cancelling, twisted-pair cabling. The ground bus was replaced with twisted-pair power cabling.

With these changes, we expect EM61 noise levels to be nominal on the next survey.

## 8.6 TRACK GUIDANCE

During the demonstration, three people operated the boat, and each used a different primary method of track guidance. One relied completely on the Trimble EZ Guide. Another relied on landmarks on the shoreline, and glanced at the traverses shown on the fish operator's station in MagLog. The third operator, who operates a variety of marine vessels for hydrographic applications, suggested that we set up his notebook computer running the commercial hydrographic package HyPack and feed it the same GPS strings being fed to the EZ Guide. Although any 17 ft boat is affected substantially by wind, wave, currents, and wake, and although the third operator, using HyPack, did the best job at line following, all three operators complained that, when correcting the boat's path and trying to bring it on track, there seemed to be a surprisingly long lag between steering correction and visible effect on the boat's course. This lag sometimes produced overcorrection. Near the end of the demonstration we determined what was causing the lag. The Trimble MS860II heading receiver—the primary geolocation instrument on the boat—has two antennas, but the position of only one of the antennas is available as an NMEA output. The other antenna's position is used internally by the receiver to calculate the heading, but it is not available as an NMEA output. USEMS minimizes geolocation errors by having that primary GPS antenna in the stern of the boat, near the pivot point of the boom. This stern-mounted location was creating the lag. We then mounted an additional GPS receiver and antenna in the bow of the boat and fed its NMEA output to the lightbar and the notebook computer running HyPack, and the line following improved dramatically.

We used the results of Oasis' "footprint coverage" tool on all of the runs on the shallow water test plot. The average missed area was 21%. The metric for this objective was having the missed area be less than 5%. By this metric, the success criteria were not met. We have the following observations:

- While wind, wave, currents, and wake place limits on the ability to follow pre-planned lines and generate survey data with high footprint coverage, an experienced operator using tools that he or she is familiar with can do much better than an inexperienced operator trying to drive while gaining familiarity with the tools.
- While MagLog's display of real-time traverses on top of the planned tracks is useful, and while the lightbar's display of an off-track indicator is useful, these should be supplemented with a small computer running HyPack or the equivalent that puts the display of both of these at the operator's fingertips. We have installed a dedicated guidance computer and a small touchscreen at the boat operator's station in preparation for the next survey.
- A GPS located in the forward section of the boat (or a simulated GPS string whose location has been translated to the bow of the boat) should supply the required NMEA strings to the guidance tools. We have made this modification in preparation for the next survey.

## 8.7 OPERABILITY BY A TWO-MAN CREW

The system was secured nightly at a slip at the marina. Although it would have been possible to leave the fish and boom in the water for the entire operation, concern over the possibility of damage by small waves beating the equipment into the pier caused us to decide to put the fish and boom in the water every morning and pull it out every evening. This was sometimes accomplished using the jib crane on the bow of the boat, but sometimes the fish was simply pulled out of the water and pulled up onto the dock by two people. Although the two people were not always the boat and fish operator, we consider the success criteria to have been met; there was no deployment or retrieval function that required a third person. Survey operations were always conducted by the fish operator (Robert Siegel) and whichever of the three boat operators who was driving. Thus the success criteria were met.

## 8.8 OPERATORS PRESENTED WITH SUFFICIENT INFORMATION

The fish operator concentrated primarily on the window in the MagLog display showing the digital numeric reading from the altimeter in the fish (e.g., 1.0 m), and nudged the joystick to keep the fish at the desired altitude. Although the real-time altimeter reading was noisy, the operator was able to "eyeball average" the data with little difficulty. It is possible to have MagLog display the difference between the boat altimeter and the fish pressure transducer to generate a stable fish height reading, but this was not necessary. Thus, for the fish operator, the success criteria were met.

The boat operator concentrated primarily on trying to keep the boat on preplanned lines. As described above, line following was difficult due to wind, wave, currents, and wake, and the

absence of a dedicated boat guidance computer, but the single largest factor affecting line following was the location of the GPS antenna feeding the guidance system. Once this was corrected, line following improved dramatically. Thus, for the boat operator, the success criteria were met. Nonetheless, we have integrated a dedicated guidance into the boat operator's station.

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# 9.0 COST ASSESSMENT

## 9.1 COST MODEL

The cost model is shown in Table 3.

**Table 3. Cost model.**

| Cost Element | Data to be Tracked | Estimated Costs |
|---|---|---|
| **Instrument cost** | Component costs and integration costs<br>• Engineering estimates based on current development<br>• Lifetime estimate<br>• Consumables and repairs | $238,000 |
| **Mobilization and demobilization** | Cost to mobilize to site<br>• Derived from demonstration costs | $14,000 |
| **Site preparation** | Test plot emplacement | $3500 |
| **Instrument setup costs** | Unit: $ cost to set up and calibrate<br>Data requirements:<br>• Hours required<br>• Personnel required<br>• Frequency required | $550<br><br>1<br>2<br>Daily |
| **Survey costs** | Unit: $ cost per hectare<br>Data requirements:<br>• Hours per hectare<br>• Personnel required | $1440<br><br>3.29<br>2 |
| **Detection data processing costs** | Unit: $ per hectare as function of anomaly density<br>Data Requirements:<br>• Time required<br>• Personnel required | $170<br><br>2 hours<br>1 |

**Instrument Cost:** Hardware cost estimates for USEMS are in Table 4. The original proposal for USEMS did not include a GPS (the project was to use SAIC's GPS at no cost). However, the use of a Trimble MS860II heading receiver simplified things substantially, so a used unit was procured. GPS antennas, radio, and base station were loaned by SAIC. The $12,000 GPS cost represents the cost to purchase a used MS860II, antennas, and a radio. Cost of a base station is not included below, as subsequent use of USEMS will probably employ corrections from an RTN as was done at Plum Tree Island. An EM61 electronics console was loaned to the project by SAIC but is included in the cost below. The magnetometer interleaving box from MSEMS was officially used in USEMS as government transferred property, but a $25,000 cost is entered as an estimate if SAIC needs to build another.

A $106,000 contract to Brooke Ocean Technology funded the design and development of the towfish (absent the sensors and electronics). The $20,000 for towfish housing represents an estimate that 20% of that cost was materials and fabrication and 80% was nonrecurring engineering costs.

Integration costs to build another USEMS from scratch are estimated as a senior project manager, mechanical engineer, and technician full time for 4 weeks, and a software engineer full time for 1 week, totaling approximately $80,000.

This results in an estimate of $238,000 for duplication costs.

**Table 4. Estimated USEMS component costs.**

| **USEMS Components** | | |
|---|---|---|
| Boat | 17 ft Carolina Skiff | $20,000 |
| Computer | Aaeon 6920 | $2500 |
| Monitor | Argonaught | $1500 |
| Towbar and bridle | Forte Carbon Fiber | $3000 |
| EM61 electronics console | Geonics | $10,000 |
| EM61 submersible coil | Geonics | $8000 |
| EM61 submersible cable | Geonics | $3000 |
| G882 Magnetometer and cabling | Geometrics | $30,000 |
| MagLog software | Geometrics | $3500 |
| Inclinometers and cabling | Advanced Geomechanics | $4000 |
| Diveplanes and hydraulics | Various | $5000 |
| Rotary positioning sensors | Penny&Giles | $1500 |
| Trimble MS860II | Trimble | $12,000 |
| Depth charter | Humminbird | $1500 |
| Towfish housing | Brooke Ocean Technology | $20,000 |
| Mag interleaving box | SAIC | $25,000 |
| Transom mount | LeCam | $2000 |
| Transom pivot | LeCam | $4600 |
| Boom attachment | LeCam | $1000 |
| **Integration** | | $80,000 |
| **Total** | | **$238,100** |

We estimate the lifetime of the system as 5 years.

It is too early to estimate repair costs. We experienced one mechanical failure at Plum Tree Island—a broken tab where the bridle attaches to the boom due to inadequate strength in the composite material. The component is being redesigned using different composite material.

Consumables are simply the fuel for the boat.

**Mob/Demob:** The cost of mobilizing USEMS from Waltham, MA, to Plum Tree Island, VA, and back, adjusted for a projected two-man crew, was approximately $13,000.

**Site Preparation:** No site preparation was necessary for the USEMS survey. If the cost of putting in the test plot is part of site preparation, a day of field time was approximately $3500.

**Instrument Setup Costs:** Instrument setup time at Plum Tree Island was approximately half a day. Thus we estimate the cost as an hour of two people, or approximately $500.

**Survey Costs:** We estimate the coverage rate, and the resulting cost per hectare, assuming six hours per day of on-the-water data collection, an average speed of 1.5 m per second, an efficiency factor of 75% (that is, 25% of the time spent turning around between lines), and a crew of two. The results are shown in the table below.

**Table 5. Coverage rate calculation.**

| | |
|---|---|
| speed (meters/sec) | 1.5 |
| hours/day | 6 |
| linear meters | 32,400 |
| efficiency factor | 0.75 |
| square meters/day | 24,300 |
| hectares/day | 2.43 |
| hours/hectare | 3.29 |
| cost/day | $3500 |
| cost/hectare | $1440 |

**Detection Data Processing Costs:** USEMS data are read into the program usemsproc for geolocation, but processing is no different from MSEMS data. Processing EM61 data is no different than processing data from a COTS EM61; the data must be de-spiked, lag-corrected, and background-leveled. These steps are performed in usemsproc. USEMS' magnetometer data requires the additional step of notch-filtering out the instrument-specific 15 Hz hum (created by the 60 Hz ambient electrical hum aliasing at 15 Hz because it is sampled at 75 Hz). This is also performed in usemsproc. The magnetometer and EM61 data are then independently read into Oasis, and thresholds are applied to the magnetometer and EM61 data to generate a mag dig sheet and an EM61 dig sheet. At present, however, there is not a turnkey method of combining these dig sheets. Different survey jobs have had different requirements. Terrestrial production surveys have tended to utilize EM61-derived target picks, with any additional unique magnetometer target picks added in by hand. However, due to the standoff of the fish from the bottom, the detection advantage clearly belongs to the magnetometer. The costs are estimated assuming that it takes one person 2 hours to batch-process one day's worth of data and generate anomaly maps and dig sheets.

## 9.2 COST DRIVERS

Deployment of USEMS requires the equipment to be strapped to the deck of the boat, and the boat, on its trailer, to be towed to a survey site. The equipment is currently based in the Northeast. As such, West Coast deployment would carry high mobilization cost. Because the equipment attracts a lot of attention when left in hotel parking lots, a private security guard is recommended.

If a USEMS area survey is conducted with a goal of detecting small munitions items, survey time and thus cost will likely increase in order to ensure coverage with very small amounts of missed area.

## 9.3 COST BENEFIT

USEMS is an alternative to cable-towed systems. It allows a towfish containing a magnetometer and an EM61 to be deployed close to the bottom and geolocated very accurately in very shallow (<12 ft) marine environments. USEMS is not intended to replace larger cable-towed arrays in open, deeper areas but is intended to augment cable-towed arrays where they may have trouble with very shallow water and entanglements with obstacles such as buoys. As such, the benefit comes from being able to survey areas where previously there was no applicable survey tool.

# 10.0 IMPLEMENTATION ISSUES

## 10.1 COTS VERSUS CUSTOM EQUIPMENT

Although all of the geophysical sensors, positioning sensors, and major subsystems in USEMS are COTS or near-COTS, USEMS as a whole is a custom-built prototype. The towfish, boom, bridle, dive planes, transom, and boom pivot with its rotary positioning sensors on all three degrees of freedom are all hand-built.

## 10.2 INTENDED OPERATORS AND TRAINING

At Plum Tree Island, the system was operated by its inventors, as is appropriate for a dem-val survey. For subsequent surveys, USEMS can be operated by a lightly trained crew consisting of a boat pilot with experience in driving parallel lines, and a geophysical technician with experience acquiring GPS, EM61, and magnetometer data in MagLog.

## 10.3 DEPLOYMENT OF TOWFISH AND BOOM

USEMS' design included the requirement that the fish and boom be able to ride on the deck of the boat until the boat reached the survey area and then deployed in the water at the survey area. In practice, we've found that the best way to deploy the fish and boom is to put them both in the water, put a USEMS operator into a small inflatable, and have him attach the fish to the boom and then the boom to the transom mount. At Plum Tree Island, we deployed the system this way every morning; it took perhaps 15 or 20 minutes. However, because the test plot was so close to the marina, we deployed the equipment dockside at the marina. It will be challenging to deploy in this fashion in rough seas. However, the greater issue is that, because of its small shallow-draft boat, USEMS is not designed for rough seas—it is designed for operation in sea states 0 or 1. For this reason, whether the equipment is deployed dockside or deployed at the survey site will be a function of the distance and the sea state.

## 10.4 USE OF GPS RTN TO ELIMINATE NEED FOR BASE STATION

Because a portion of the demonstration included surveying off Plum Tree Island, and because Plum Tree Island is a restricted area, it was necessary to develop a solution for GPS deployment that did not require physically placing a base station on Plum Tree Island. For this reason, we utilized an RTN solution that accessed RTK corrections available over the Internet. This worked well. However, for a subsequent survey, we would not use a thumb-sized USB cellular modem and would instead employ one of the models utilizing a more sensitive external antenna.

## 10.5 LINE FOLLOWING

The ability to follow preplanned lines on the shallow water test site turned out to be the major challenge of the demonstration. We have outfitted the boat with a small computer capable of running a general hydrographic survey and planning, and a display and guidance package such as HyPack, accessible via a touchscreen mounted at the boat operator's station so the boat operator can interact with it in the same way he or she interacts with the chart plotter—that is, to choose among the myriad of configurable display options, depending on what he or she wishes to see. In

the sea state 0 or 1 conditions for which USEMS was designed, when piloted by experienced operators with proper guidance tools, USEMS is expected to do a good job at area coverage.

## 10.6 USEFULNESS OF EM61 DATA VERSUS MAGNETOMETER DATA

In terrestrial MEC survey work where the majority of items are shallow, their size is small to medium, and sensors can be deployed very close to the ground, pulsed EM sensors (particularly the EM61) have been the sensor of choice for nearly 15 years. Magnetometers continue to be the sensor of choice for high-standoff applications such as airborne or underwater where their 1/R3 response is necessary (an EM sensor's 1/R6 response makes it less well suited than a magnetometer for high-standoff applications of ferrous objects). Because USEMS simultaneously deploys both a magnetometer and an EM61, we are able to see the response of both sensors in the underwater environment. In the shallow test plot, the standoff above bottom was small (about 0.5 meters); thus most objects were readily detectable by both sensors. On the deep test plot, where we collected data at standoffs of 1.0 and 1.5 m, the signatures in the EM61 data became vanishingly small. In a signal-to-noise sense, this was caused by both the high EM61 noise present on the Plum Tree Island survey, as well as the decreased signal from the 1.0 and 1.5 m sensor standoff. Since the Plum Tree Island survey, we have made modifications to the boat and EM61 wiring that have dramatically reduced the EM61 noise levels. For this reason, we expect EM61 noise levels to be nominal on the next survey.

On a terrestrial survey, if the target of interest is nonferrous or low-ferrous (e.g., 20 mm or 40 mm projectiles), then the EM61 is the sensor of choice for detection. However, even on a terrestrial survey, reliable detection of these objects requires careful adherence to data quality objectives such as reduced sensor height, line spacing, missed area, and noise. This demonstration survey has shown that maintaining those particular data quality objectives is challenging in the underwater environment.

## 10.7 HEIGHT OSCILLATIONS

It is likely that the slight height oscillations that appeared to be present in very shallow water can be corrected prior to the next survey. If the oscillations are a function of the towfish being in the motor's propeller wash, it is possible that simply angling the motor upward or installing a jack plate may mitigate the problem.

## 10.8 REGULATORY ISSUES

Since the sensors (magnetometer and EM61) are already accepted by the regulatory community, there should be no regulatory hurdles to acceptance and use.

## 10.9 CURRENT AVAILABILITY OF THE TECHNOLOGY

USEMS is government-owned and is ready for field use.  It can be provided as government furnished equipment to DoD contractors but would require trained operators. The developers from SAIC should be part of any survey teams in the first deployments of this system, either as prime contractor or as a subcontractor to another DoD prime contractor.

## 11.0 REFERENCES

Siegel, Richard, and Schwartz, "USEMS Final System Design Document," 2009. (Can be provided upon request.)

Siegel, Enriquez, "Underwater Simultaneous EMI and Magnetometer System," MR-200733 Final Report, 2011.

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# APPENDIX A

# POINTS OF CONTACT

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